LARES  
(LAser RElativity Satellite)  
and  
MoonLIGHT  
(Moon Laser Instrumentation for General relativity High-accuracy Tests)  

S. Dell’Agnello (INFN-LNF)  
for the LARES Collaboration  
and  
for the MoonLIGHT Collaboration  

Vulcano Workshop, May 2008
Outline

• High-accuracy tests of General Relativity

• Tests of General Relativity with LAGEOS and LARES
  – Effect of thermal non gravitational perturbations (NGPs)

• Testing Torsion with LAGEOS and LARES

• MoonLIGHT: project of NASA LSSO program
  – New concept for 2nd generation Lunar Laser Ranging
  – Tests of General Relativity
  – Testing Brane Worlds and deviations from $1/r^2$

• MAGIA: ASI Phase Study for a Small Mission
  – Gravitational Redshift and synergy with MoonLIGHT

• Conclusions
High-accuracy tests of General Relativity (GR)

• Observation of Gravitational Waves is the most important dynamical test

• **Main theoretical goal**
  – Quantum Gravity and Unification of the four interactions
  – GR is a classic theory; singularities; cannot be the ultimate theory

• **Main experimental goal**
  – Where does GR fail? At what accuracy?
  – Dragging of space time by central rotating mass (Lense-Thirring effect)
    • LAGEOS: 10%
    • Gravity Probe B: goal was 1%; 300% @APS07, now 30%?
    • LAGEOS+LAGEOS II+LARES: goal is 1%
  – Space-time curvature: VLBI, Cassini; PPN $\gamma$
  – Geodetic/De Sitter precession of the Moon: Lunar Laser Ranging; PPN $\beta$
    • MoonLIGHT
  – Gravitational Redshift/Shapiro time delay: Gravity Probe A, Vikings; PPN $\gamma$
    • MAGIA

• **New theories**: Torsion, Brane Worlds, $1/r^2$-deviations
The LARES Collaboration

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The LAGEOS / LARES three-satellite experiment

LAGEOS I: 1976; NASA
LAGEOS II: 1992; NASA-ASI

LAGEOS: Al with Brass core
Ø=60 cm, 400 Kg, 426 CCRs

LARES: full W-alloy,
Ø=38 cm, 400 Kg,
92 CCRs

NGPs ∝ Area/Mass

M_{LARES} \sim M_{LAGEOS} \sim 400Kg
M/S_{LARES} / M/S_{LAGEOS} \sim 2.7

LARES: ASI-ESA
Launch with VEGA
LAGEOS+LARES vs Gravity Probe B

LAGEOS, LAGEOS II & LARES:
dragging of orbital angular momentum wrt ITRF. Passive satellites

\[ \dot{\Omega}_{L-T} = \frac{2GJ}{c^2 a^3 (1-e^2)^{3/2}} \]

Nodal rate, \( d\Omega/dt \sim 2 \text{m/yr} \)

Gravity Probe B:
dragging of gyroscopes wrt distant guide star IM Pegasi. Very high-tech spacecraft.
NASA mission ended in 2006

Costs: LARES, few M€; GP-B, 760 M$
SCF-Test of the LAGEOS eng. proto from NASA-GSFC

Thermal and laser ranging tests never performed before in space conditions
Our 1st published paper: effect of thermal NGPs

Thermal NGP error on Lense-Thirring effect driven by CCR thermal relaxation time ($\tau_{CCR}$)

- $\tau_{CCR}$ never measured in space conditions.
- $\tau_{CCR}$ predictions vary by 350% (2000-7000 s)

$\sigma(\tau_{CCR})/\tau_{CCR} = 350\%$ would give on the measurement of the Lense-Thirring effect an error of 3 %, compared to the 1% LARES goal

In addition (not in the paper at left):
unmodelled spin rate and spin direction give additional significant experimental NPG error on Lense-Thirring
LAGEOS: Thermal SCF-Test and simulation (tough job)

Our measurement:
\[ \sigma(\tau_{CCR}) \sim 10\% \text{ at } T \sim 300\text{K} \]
makes effect of thermal NGPs negligible on measurement of Lense-Thirring effect

Temperature vs time of CCR and mounting rings

SCF work led by
G. O. Delle Monache
General Relativity with Torsion: GP-B

Constraining Torsion with Gravity Probe B

Yi Mao, Max Tegmark, Alan H. Guth, and Serkan Cabi

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(Dated: Submitted to Phys. Rev. D. 1/8-07; Revised 9/18-07; Accepted 9/27-07)

It is well-entrenched folklore that all torsion gravity theories predict observationally negligible
torsion in the solar system, since torsion (if it exists) couples only to the intrinsic spin of elementary
particles, not to rotational angular momentum. We argue that this assumption has a logical loophole
which can and should be tested experimentally, and consider non-standard torsion theories in which
torsion can be generated by macroscopic rotating objects. In the spirit of action–reaction, if a
rotating mass like a planet can generate torsion, then a gyroscope would be expected to feel torsion.
An experiment with a gyroscope (without nuclear spin) such as Gravity Probe B (GPB) can test
theories where this is the case.

Using symmetry arguments, we show that to lowest order, any torsion field around a uniformly
rotating spherical mass is determined by seven dimensionless parameters. These parameters ef-
tectively generalize the PPN formalism and provide a concrete framework for further testing GR.
We construct a parametrized Lagrangian that includes both standard torsion-free GR and Hayashi-
Shirafuji maximal torsion gravity as special cases. We demonstrate that classic solar system tests
rule out the latter and constrain two observable parameters. We show that Gravity Probe B is
an ideal experiment for further constraining non-standard torsion theories, and work out the most
general torsion-induced precession of its gyroscope in terms of our torsion parameters.

Missing in this paper is the effect of Torsion on the
orbital angular momentum of LAGEOS & LARES …
General Relativity with Torsion: LAGEOS+LARES

G. Bellettini, R. March, R. Tauraso, S. Dell’Agnello, ….

In the following: correction to Lense-Thirring only

Using the Lagrange planetary equations of perturbation theory, and denoting by $\Omega$ the longitude of the node, we find

$$\dot{\Omega} = \frac{2J}{a^3(1-e^2)^{3/2}} \times \left(1 - \frac{G + 2}{2} - \frac{w_2 - w_4}{4}\right),$$

\hspace{1cm} (1)

$$\dot{\Omega} = \dot{\Omega}_{LT} \times (1 + PERT), \quad PERT = -\frac{G + 2}{2} - \frac{w_2 - w_4}{4}$$

$a$ and $e$ being the (unperturbed) semimajor axis and eccentricity, and $\dot{\Omega}_{LT} = \frac{2J}{a^3(1-e^2)^{3/2}}$ is the unperturbed Lense-Thirring rate.

- **When there is no torsion** $w_2 = w_4 = 0$. When in addition $G = -2$, the metric is the weak field approximation of the Kerr metric, $PERT = 0$ and (1) becomes the classical Lense-Thirring equation.
- **Measuring $\dot{\Omega}$ at 1% relative accuracy with LARES and the two LAGEOS will allow for setting a limit on the combination of torsion parameters $PERT$ of the order of 1%.
Limits on Torsion with measurement of frame dragging

LAGEOS+LARES sensitive to combo of parameters \( \Rightarrow w_2 - w_4 + \ldots \)

GP-B sensitive to different combo \( \Rightarrow w_1 + w_2 - w_3 - 2w_3 + w_5 \)

Limit by Mao, Guth et al for GP-B in figure assumes a relative error on Lense-Thirring of \( \sim 1\% \)

With April 07 GP-B error \( (~300\%) \) the allowed band (hatched) is way off-scale.

With LAGEOS only, the \( w_2-w_4 \) allowed band is of order of 10\%
The MoonLIGHT Collaboration

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NASA “Lunar Sortie Scientific Opportunities” (LSSO) Program
Call “Suitcase Science to the Moon” for manned landings:
77 proposals; 11 approved; 3 out of 11 on Lunar Laser Ranging by

1) NASA-JPL
2) NASA-GSFC
3) U. of Maryland / INFN-LNF == MoonLIGHT

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APOLLO Lunar Laser-Ranging Observatory (T. Murphy et al), Los Alamos, USA
Affected by \textit{geometric} Libration of the Moon (LLR accuracy $\sim$ cm)

$\sim$30 cm $\times$ 30 cm \textbf{matrix} array (100+ tightly-spaced CCRs)

Unaffected by \textit{geometric} Libration of the Moon (LLR accuracy $\geq$ 0.1 mm)

$\leq$ 100 m $\times$ 100 m \textbf{sparse} array (single very large CCRs)
Lunar Laser Ranging

1 widened pulse back to Earth due to tight CCR spacing and lunar geometric librations

3 separated pulses back to Earth

ΔT

Pulse to Moon  Pulse back to Earth  time

Old Apollo small CCRs

MoonLIGHT big CCRs

ΔT  

time

Pulse to Moon  Pulses back to Earth  time

T_1  

T_2  

T_3
General Relativity Science Objectives
(for up to factor 100 improvement over current LLR)

Table by T. Murphy

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Current limit</th>
<th>Limit with 1 mm ranging</th>
<th>Limit with 0.1 mm ranging</th>
<th>Measurement timescale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak Equivalence Principle ($\Delta a/a$)</td>
<td>$10^{-13}$</td>
<td>$\sim 10^{-14}$</td>
<td>$\sim 10^{-15}$</td>
<td>2 yr</td>
</tr>
<tr>
<td>Strong EP (Nordvedt param.)</td>
<td>$4 \times 10^{-4}$</td>
<td>$\sim 10^{-5}$</td>
<td>$\sim 10^{-6}$</td>
<td>2 yr</td>
</tr>
<tr>
<td>Gdot/G</td>
<td>$10^{-12}/yr$</td>
<td>$\sim 10^{-13}/yr$</td>
<td>$\sim 10^{-14}/yr$</td>
<td>4 yr</td>
</tr>
<tr>
<td>Geodetic Precession (PPN parameter $\beta$)</td>
<td>$\sim 5 \times 10^{-3}$</td>
<td>$5 \times 10^{-4}$</td>
<td>$\sim 5 \times 10^{-5}$</td>
<td>6-10 yr</td>
</tr>
<tr>
<td>Deviations from $1/r^2$ (Yukawa param. $\alpha$)</td>
<td>$10^{-10} \times$ gravity</td>
<td>$\sim 10^{-11}$</td>
<td>$\sim 10^{-12}$</td>
<td>6-10 yr</td>
</tr>
</tbody>
</table>

The golden measurement

LLR data triggered 2000 papers 10000 refs
Limits on non-newtonian gravity from SLR/LLR

Current limits on additional Yukawa potential:
\[ \alpha \times (\text{Newt-gravity}) \times e^{-r/\lambda} \]

MoonLIGHT ranging accuracy of 100 µm

LARES orbit radius of 8000 Km

LARES limit by I. Ciufolini
MoonLIGHT limit: current LLR limit x 10^{-2}
“BraNe new world”: a quantum theory beyond General Relativity

This Brane world theory gives anomalous precession of the Moon of ~1 mm/orbit, in addition to standard GR geodetic precession.

LLR accuracy now ~ 1 cm. New laser station APOLLO is reaching few mm.

This model can be fully tested by MoonLIGHT with 100 μm (or less) accuracy, i.e. w/factor 100 (or more) improvement over current LLR.
NASA call: “Suitcase” science to the Moon

By Astronaut Roberto Vittori. Manned NASA missions, 2015-18

Retro-reflector: 10 cm diam.
Box: 14 cm side

Suitcase for the CCR boxes (mm)

Box locks very firmly on a slide

Metal alloy: INVAR or ULE
Payload installation on the surface

By LLR “veteran” D.G. Currie of UMCP

**Innermost layer:**
- high VISIBLE reflectivity
- high IR absorptivity

**Outermost layer:**
- somewhat low VIS. Absorptivity
- low IR absorptivity; perhaps gold

**Multi-Layer Insulation**

**Thermal blanket insulation**

**REGOLITH**

Foot in a hole into regolith. Best if into rock below 0.50 m of regolith ($\Delta T \sim 2$ K)

**Top surface:**
- low VISIBLE absorption
- high 10 $\mu$m emissivity
Preliminary payload thermal analysis: CCR

CCR thermal gradient under: $\Delta T < 2$ K $\Rightarrow$ variations of the index of refraction seems OK; BUT SOON WE WILL KNOW FOR SURE WITH AN SCF-Test of the FLIGHT PAYLOAD @INFN

![Temperature graph showing retro-reflector temperature over time with T(face) = 139.2 K and T(corner) = 137.4 K]
MoonLIGHT CCRs as Moon landmarks

- MoonLIGHT units can also be used to land-mark sites and pathways of the new lunar exploration, like the Roman “milestones”
  - Toward a standard payload package for the surface of the Moon?

MoonLIGHT landmarks:
light, passive and last for many decades
Lunar orbiter MAGIA (“just approved” Phase A study)

Planetology mission and GR tests. Candidate for an ASI “Small Mission”
INFN-LNF responsible for SLR/LLR payloads for tests of GR

GR tests with MAGIA

1) Gravitational redshift
   - Retroreflectors
   - Atomic clock

2) Independent position of Selenocenter wrt ITRF

3) MoonLIGHT precursor mission (synergy with NASA)
Conclusions

• SLR/LLR is the most precise .AND. cost-effective way to probe gravity in our home laboratory, the Solar System
  – (Millimeters to 1-2 Centimeters) .AND. (0.1 M€ to M€)

• We developed a new standard: the space characterization of SLR payloads, which is an important new tool for
  – Experimental tests of Gravitation
  – Space Geodesy
  – GALILEO

• With Satellite and Lunar Laser Ranging we love to test:
  – General Relativity
  – GR with Torsion
  – Yukawa deviations from $1/r^2$
  – BraNe New Worlds
Next laser ranging frontier: MARS

• What physics?
  1) similar to the Moon (see Dvali et al)
  2) Shapiro time delay w/VIKINGS (70s)

• Technically feasible: NASA-GSFC laser transponder experiment done with MGS 100 millions of Km way

• Dust storms a problem? Rovers Spirit & Opportunity say no!

• Next lander should have CCRs !!

MOLA-Earthlink Experiment
at NASA’s 1.2 meter telescope
J. Abshire, X. Sun, G. Neumann, J. McGarry,
T. Zagwodzki, P. Jester, + many others

Experiment Objectives - Demonstrate:
• Laser pulse detection at Mars distances
  Assess Earth laser to Mars orbit detection probabilities
• Laser communications at ~ 100 Mkm distance

Mars Global Surveyor
Mars Orbiter Laser Altimeter

Courtesy of Jan MacGarry
ILRS05 workshop
Satellite Laser Ranging in deep space: the proposed Deep Space Gravity Probe mission

- Active spacecraft and passive test-mass
- Objective: accurate tracking of the test-mass
- 2-step tracking: common-mode noise rejection
  - Radio: Earth → spacecraft
  - Laser: spacecraft → test-mass
- Flexible formation: distance may vary
- The test mass is at an environmentally quiet distance from the craft, > 250 m
- Occasional maneuvers to maintain formation
Other manifestations of frame dragging

Spin-time delay and gravitational lensing: can be observable on large scale structures (I. Ciufolini)

Gravitomagnetic clock effects near spinning astrophysical objects

Ciufolini and Ricci - 2001